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1.3 μm photoluminescence emission from InAs/GaAs quantum dots multilayer structures

V. A. Egorov†‡, V. N. Petrov†‡, N. K. Polyakov†‡, G. E. Cirlin†‡,
B. V. Volovik‡, A. E. Zhukov‡, A. F. Tsatsul'nikov‡ and V. M. Ustinov‡
† Institute for Analytical Instrumentation RAS,
Rizhsky 26, 198103, St Petersburg, Russia
‡ Ioffe Physico-Technical Institute, St Petersburg, Russia

Abstract. Optical properties of multilayer structures with quantum dots InAs on GaAs are investigated. It is shown that under optimal growth conditions the 1.3 μm emission could be achieved. Possible scenarios of quantum dots behaviour evaluation is discussed in a frame of elastic theory to explain differences in optical properties of the grown structures.

Introduction

During the last decade one of main trend in the fundamental and applied surface science is an investigation of nanostructures formation processes via exploring of the self-organisation effects during heteroepitaxial growth in lattice mismatched systems. These nanostructures — quantum dots (QDs) and quantum wires — reveals ways for design the new generation of optoelectronic devices. One of the problem in modern optoelectronic is a creation of laser diodes emitted at 1.3 μm wavelength for the applications in fibre-optic communications. To solve this problem were suggested and realised several approaches: using of InGaAsN quantum wells with low nitrogen concentration in an active region [1], placing of InAs QDs in a silicon matrix [2], and realisation of the Stranski–Krastanow growth mode for QDs formation in heteroepitaxial (In,Ga)As/GaAs system allowing to shift significantly emitting wavelength in comparison to (In,Ga)As/GaAs quantum wells.

For the last case the possible ways of reaching 1.3 μm range wavelength are:

(a) InGaAs/GaAS QDs formation by depositing sufficiently high amount (~11 monolayers (MLs) for solid solution (In,Ga)As) during molecular–beam epitaxy (MBE) via supplying of In and Ga atoms and As molecules consequently in order to increase nanoisland lateral sizes [3];

(b) placing of InAs QDs in an external (Al,In,Ga)As quantum well [4, 5] which stimulates dissociation of the solid solution and leads to increased In concentration near QD.

However, the problem to achieve 1.3 μm range for structures with InGaAs/GaAs QDs is that the total InAs amount in active region is relatively high which leads to high probability of the dislocations formation. Thus, it is actual to find new ways to create devices based on QDs emitting at 1.3 μm by minimisying In amount in active region. In this paper we propose to use submonolayer migration enhanced epitaxy (SMEE) and their combination with MBE to form InAs QDs in multilayer structures allowing to observe 1.3 μm PL emission at room temperature.

Experiment

Growth experiments are carried out using EP1203 setup on singular and 7° misoriented towards [0$\bar{1}$1] and [010] directions semi–insulating GaAs(100) substrates. The samples (singular and vicinal) mounted with In on the same molybdenum holder in order to minimise heater temperature field inhomogenity and flux gradients. After desorption of an oxide layer in growth chamber at substrate temperature $T_S \approx 630$°C under As_4 flux the GaAs buffer of 3000 Å thickness is grown by conventional MBE at $T_S \approx 550$°C (2×4 surface reconstruction). Active region is placed in between 60 Å GaAs layers from both sides and consists of ten InAs QDs layers grown by SMEE or MBE+SMEE methods. For SMEE, In and As are deposited on the surface consequently, every cycle of In atoms deposition corresponds to the growth of 0.5 ML followed by 10 seconds growth interruption under As flux supplying.

Quantum dots layers are separated by 80 Å GaAs spacers. For different structures effective thickness of InAs QD layer is varied from 2.5 to 3.0 MLs. Growth temperatures $T_S \approx 480$°C for an active region (surface reconstruction 2×2 appears) and $T_S \approx 550$°C for the other parts of the structure are used. QDs formation is controlled *in situ* by RHEED technique using special registration and analysis system. Total arsenic pressure in growth chamber for all experiments are 1.5×10^{-6} Pa. Growth rates are 0.1, 0.24 and 0.7 ML/sec for InAs, AlAs and GaAs, respectively.

For PL study, active region is confined by $Al_{0.25}Ga_{0.75}As$/GaAs short-period superlattices (5 pairs, 25 Å/25 Å) from both sides. For measuring PL spectra Ar^+ laser ($\lambda =$ 514.5 nm, excitation density $\sim$100 W/cm^2) and cooled Ge photodiode as a detector are used.

Results and discussion

In Fig. 1(a) PL spectra at 77 K and 300 K for the sample which active region consisted of 10 InAs QD layers with 2.5 ML nominal thickness are shown. QDs are grown by SMEE method (5 cycles) and were separated by 80 Å GaAs spacers. Spectra are characterised by typical for quantum dots wide lines with maximuma at $\sim$1.2 eV and $\sim$1.05 eV for 77 K and 300 K, respectively. At room temperature only long-wave edge of PL line is in 1.3 μm region. A conclusion about relatively small nanoisland sizes from these spectra is made. This may be explained either by partial evaporation of In atoms during SMEE first cycle (which leads to effective decrease of InAs layer nominal thickness) or by effective migration of adatoms during exposing in As cycle.

To clarify the situation a serie of multilayer structures with different technological parameters is grown. Increasing InAs amount in each QD layer up to 3.0 ML leads to shift PL peak towards long-wave region. However, the shifting is accompanied with dramatically PL intensity decreasing in comparison to the previous structure. In this case only the small part of QDs with the sizes satisfying 1.3 μm emission is formed. Most of the nanoislands exceed critical volume of misfit dislocations formation and as a result — crystallographic quality of the whole structure worses.

But if the first cycle (0.5 ML of InAs) is grown by conventional MBE and the others — by SMEE (2.5 ML of InAs in total for each layer) situation changes. In Fig. 1(b) PL spectra taken at 77 K and 300 K for singular and vicinal samples are shown. At 77 K PL spectra are characterised by set of peaks in 1.0–1.2 eV range with typical shift to short-wavelength region for vicinal samples [6].

Coexistence of several peaks on these spectra causes by several reasons: presence of

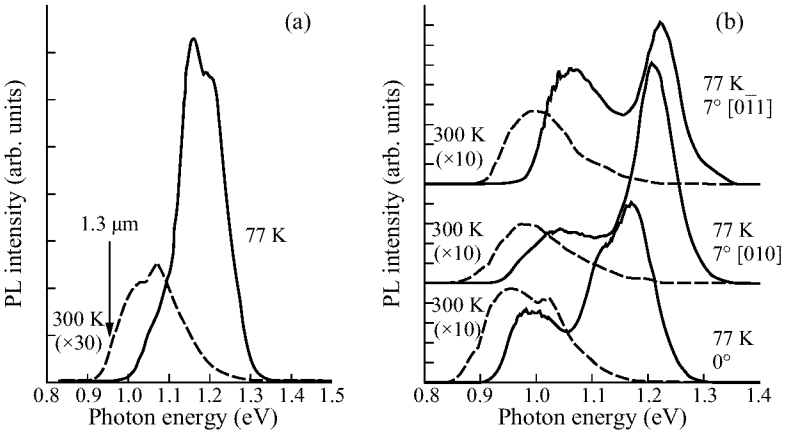

Fig. 1. PL spectra taken at 77 K (solid line) and 300 K (dashed line). (a) Active region consists of 2.5 ML of InAs QDs grown by SMEE (10 QDs sheets). (b) Active region consists of 0.5 ML of InAs grown by MBE + 2.0 ML of InAs grown by SMEE (10 QDs sheets).

several groups of QD with different sizes, possible formation of QD conglomerates in upper layers as a result of lateral association of neighbour QDs [7], or contribution of excited states of QDs which is proved by changing the spectrum shape at lower excitation density. At room temperature maximum of PL peak for singular sample is at 1.3 μm, for vicinal samples — at 1.20–1.25 μm which is also correlating with PL data at 77 K. Relatively low intensity decreasing at 77 K and 300 K (about 10–20 times) reveals high quality of the grown structures.

Computer simulation data [8] of the multilayer structures with QDs formation during MBE based on elastic interaction theory show following different behaviour in vertically stacked nanoislands system depending on the nanoisland spacing:

(a) increasing of the nanoislands size from layer to layer with further association,

(b) new nanoisland birth with slight size decreasing,

(c) equilibrium state of the system with multilayered QDs for the stacking of the islands upon each other from layer to layer.

These scenarios depend critically on the spacer thickness between different layers. For the described above structures the interval of nanoisland spacing in order to get high crystallographic quality of structure should be ~240–400 Å which is in accordance with our previous STM study [9].

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